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INTERACTION OF COPPER-CONTAINING ROTATING BAND METAL WITH GUN BORES AT THE ENVIRONMENT PRESENT IN A GUN TUBE

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Watervliet, New York

June 1974

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The nickel-based, cobalt-containing high temperature alloys now being considered for barrels for rapid-firing aircraft weapons could be seriously affected by interaction with copper-containing rotating band metal. Copper and nickel form a continuous series of solid solutions so copper could interact with the bore metal at the high operating temperatures planned for the new alloy barrels with the formation of low-melting, easily-eroded surface layers. Furthermore, there is the possibility that molten copper will cause liquid-metal

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Block No. 20   ABSTRACT(Continued)

embrittlement because of the cobalt content of the alloys. 4340 Steel, Pyromet
X-1ʺ. C. G 27, René 41, and Udimet 700 were studied with sessile-drop experi-
ments and firing experiments which simulated conditions in the bore of a rapid-
firing gun.

It was found that, although C. G. 27, René 41, and Udimet 700 all inter-
acted strongly with copper in sessile-drop experiments, only René 41 showed
any interaction with copper alloy in the firing experiments. The contact
times were very short in these experiments even if the test bore surface
remained above the melting point for gilding metal during the latter part of
the burst. René 41 exhibited severe erosion which was shown to be the result
of interaction with the copper alloy although copper had not penetrated into
the René structure. Udimet 700, on the other hand, showed strikingly little
erosion even at a higher initial temperature and a much longer burst length.

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INTERACTION OF COPPER-CONTAINING
ROTATING BAND METAL WITH GUN BORES
AT THE ENVIRONMENT PRESENT IN A GUN TUBE

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JUNE 1974

TECHNICAL REPORT

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Erosion of gun bores near the origin of rifling is usually attributed entirely to the action of hot propellent gases. [1] While jackets for small arms bullets and rotating bands for artillery projectiles are commonly made of gilding metal (a binary alloy of copper and zinc containing 90% copper) participation of copper in the erosion is considered unimportant. This is doubtless true for conventional steel barrels, even though molten copper has been found to embrittle iron by grain boundary penetration [2], because rotating bands of copper alloy have given satisfactory service with steel barrels for a great many years. However, it is not necessarily true for the advanced, high temperature alloys which are now being considered for barrels for rapid-firing guns. Modern high sustained rates of fire require gun tubes which will allow high operating temperatures without serious erosion and with little danger of bursting. Most of the alloys which are being considered for these barrels are nickel and cobalt-based and have been selected on a basis of their mechanical properties at high temperatures and possible interaction with copper-containing rotating band metal has not been considered.

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[1]Zies, E. G. and Marsh, C. A., "The Products of Gun Erosion", Hypervelocity Guns and the Control of Erosion, Summary Technical Report of Division I, NDRC, 244 (1946)

[2]Hough, R. R. and Rolls, R., "Creep Fracture Phenomena in Iron Embrittled by Liquid Copper", J. Materials Science 6, 1943 (1971)

It is possible that nickel-based alloys could interact with copper from the rotating bands with the formation of low-melting, easily-eroded surface layers at the high operating temperatures planned for the new alloy barrels. While the solubility of copper in γ-iron is somewhat below 8 weight percent at 2000°F and is 4 weight percent at 1562°F [3], copper and nickel form a continuous series of solid solutions. [4] The environment in a gun tube during firing is near ideal for bore metal-copper interaction. Research conducted during World War II showed that there was little doubt of the, at least partial, fusion of the bore surface during firing, and melting of a number of nonferrous alloys used experimentally was observed. [5,6] Furthermore, the surfaces of the rotating bands melt and, after extended firing, much of the bore is often covered with well-bonded deposits of copper alloy. [6] Therefore, bore metal is in intimate contact with molten copper alloy at the high temperature and under the severe mechanical working which occurs at the origin of rifling during firing. Under these

[3] Hansen, Max, "Constitution of Binary Alloys" 2nd Ed., p. 580. McGraw-Hill Book Co., New York City (1958)
[4] Ibid, P. 601
[5] Heyl, P. R., "Investigation of the Control of Erosion in Guns and the Improvement of Gun Performance", NDRC Report A-467 (1946)
[6] Line, L. E., Jr., "Description of Eroded Gun Bores" Hypervelocity Guns and the Control of Erosion, Summary Technical Report of Division I, NDRC, 195 (1946)

conditions, copper could interact with the gun bore metal. Indeed, this was stated to have occurred in the experiments of Harlow and Kimball with a barrel of the nickel-based René 41. [7] In their experiments, extended bursts were fired from a 7.62mm caliber machine gun fitted with a barrel of one of the test alloys. Catastrophic erosion occurred with the René 41 barrel. It was most severe in the hottest portion of the barrel but there was very little rifling left over its entire length. The authors stated that the copper from the bullet jackets had alloyed with the René 41, effectively lowering its melting point and allowing the bore surface to be literally "wiped away".

In addition to this possible interaction of nickel-based alloys with copper, there is also the possibility that cobalt-containing alloys will be degraded by molten copper. Matthews, et al [8] found that barely discernible amounts of copper transferred to the surfaces of high-cobalt alloys result in gross microcracking during welding. The cracking mechanism appears to be separation along grain boundaries with little evidence of plastic deformation of the grain edges. This mode of failure is reminiscent of classic cases of adsorption-induced liquid-metal embrittlement.

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[7]Harlow, R. A. and Kimball, R. C., "Aeronutronic Advanced Gun Barrel Development Program", Symposium on Gun Tube Erosion and Control, Watervliet Arsenal, Watervliet, N.Y., Feb 25, '70.
[8]Matthews, M.O. et al, "How Copper Surface Contamination Affects Weldability of Cobalt-Superalloys", Welding Journal, May 1972, p. 326.

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BORE METALS STUDIED

Two iron-based and three nickel-based alloys were studied; one of the iron-based and two of the nickel-based alloys also contain significant amounts of cobalt. Compositions of these alloys are given in Table I. 4340 Steel was included in the test program to serve as a control for the experiments with the high-temperature alloys; it is very similar to conventional gun steel.

Pyromet X-15 is a high-strength, low-carbon martensitic stainless steel containing 20 weight percent cobalt. Harlow and Kimball[7] found that machine gun barrels of this alloy had somewhat better erosion resistance than those of gun steel but were not as good as those of the superalloys. Copper embrittlement could be a problem with this alloy because significant cracking was found during welding of Multimet(N-155) which also contains 20 weight percent cobalt. [8]

Crucible Steel's C. G. 27, an iron-nickel alloy, gave the best performance of the three bore metals tested by Gruner [9] using the 30mm aircraft cannon. A total of 4500 to 5000 rounds were fired and the barrels subjected to

[7]Harlow, R. A. and Kimball, R. C., "Aeronutronic Advanced Gun Barrel Development Program", Symposium on Gun Tube Erosion and Control, Watervliet Arsenal, Watervliet, N.Y., Feb 25, '70.
[8]Matthews, M.O. et al, "How Copper Surface Contamination Affects Weldability of Cobalt-Superalloys", Welding Journal, May 1972, p. 326
[9]Gruner, F. R., "A High Performance Automatic Aircraft Cannon Barrel", Symposium on Gun Tube Erosion and Control, Watervliet Arsenal, Watervliet, N. Y., Feb. 25, 1970.

TABLE I – Chemical Compositions of the Test Alloys

	4340 Steel	Pyromet X-15	CG27	René 41	Udimet 700
Iron	balance	balance	balance	5.0% max	---
Nickel	1.65 - 2.0%	0.20% Max.	38%	balance	balance
Cobalt	---	20.	---	11.	15. - 20.%
Carbon	0.38 - 0.43	0.03 max.	0.05	0.12 max	0.05 - 0.10
Chromium	0.7 - 0.9	15.	13.	19.	15.
Molybdenum	0.2 - 0.3	2.9	5.75	10.	5.
Manganese	0.55 - 0.85	0.10 max.	---	---	---
Silicon	0.20 - 0.35	0.10 max.	---	---	---
Aluminum	---	---	1.6	1.5	4.4
Titanium	---	---	2.5	3.2	3.4
Boron	---	---	0.01	0.007	0.03
Columbium	---	---	0.7	---	---

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abnormally long continuous bursts lasting a minute to a minute and a half. There was severe erosion at the conclusion of the test but the C.G. 27 barrel had performed very satisfactorily under these conditions.

René 41 is a nickel-based high-temperature alloy containing 11 weight percent cobalt. This level of cobalt should not lead to a copper embrittlement problem. In the experiment of Harlow and Kimball [7], a machine gun barrel of this alloy showed no erosion after five 600 round bursts while conventional gun steel eroded seriously after a single 400 round burst and failed after three 400 round bursts. However, as mentioned above, catastropic erosion occurred during an exploratory 800 round burst with ver little rifling remaining over the entire length of the barrel. The investigators attributed this to copper from the bullet jackets alloying with the René which effectively lowered its melting point and made it extremely susceptible to erosion. In the experiments reported by Gruner [9], a 30mm aircraft cannon barrel showed an 18 percent drop in muzzle velocity on being fired for a 460 round continuous burst and after another burst of 560 rounds showed a permanent bulge in the

[7]Harlow, R. A. and Kimball, R. C., "Aeronutronic Advanced Gun Barrel Development Program", Symposium on Gun Tube Erosion and Control, Watervliet Arsenal, Watervliet, N.Y.,Feb 25, '70.
[9]Gruner, F. R., "A High Performance Automatic Aircraft Cannon Barrel", Symposium on Gun Tube Erosion and Control, Watervliet Arsenal, Watervliet, N. Y., Feb. 25, 1970.

barrel as well as severe erosion. Evidently, the interaction
of molten gilding metal with this alloy leads to serious
erosion.

Udimet 700 is a nickel-based, cobalt-containing alloy.
Its 15-20 weight percent cobalt content could result in some
copper embrittlement. It has been considered as a barrel
metal because of its excellent mechanical properties at high
temperatures but, to my knowledge, has not been studied in
actual firing tests.

The melting range of the 4340 steel is 2645° - 2740°F
while that of X-15 stainless steel is 2660° - 2675°F. The
melting ranges of the nickel alloys are Rene 41, 2385° -
2450°F; C.G. 27, 2450° - 2510°F; and Udimet 700, 2220° -
2550°F. Therefore, the reported superior erosion resistance
of these metals cannot be the result of higher melting
temperatures f the bore surfaces.

SESSILE-DROP EXPERIMENTS

Sessile-drop experiments were carried out in order to
determine the extent and character of interactions b /een
molten copper and the bore metals studied. In these experi-
ments, contact times were much in excess of the contact
times between rotating bands and the bore of a cannon
throughout its entire life. However, the results should
provide a guide to the interaction to be expected with the
much shorter contact times.

Copper was used in the experiments rather than gilding metal which is the actual metal of rotating bands and bullet jackets. This was done because the apparatus available operated under vacuum and, when gilding metal was used, zinc distilled from the alloy covering the glass observation window and obscuring the specimen. Not only did this prevent measurement of contact angles but the molten metal remaining in contact with the specimen was greatly depleted in zinc. The zinc content of the gilding metal was reduced to 2 weight percent in less than two minutes at its melting point. The apparatus could have been altered to allow operation with an inert gas rather than vacuum but it was thought that the use of unalloyed copper would not affect the results significantly.

The procedure used in the experiment was as follows: A piece of copper was placed on a metallographically polished plate of the metal to be studied and inductively heated to its melting point (2000°F) under a vacuum. The plate was carefully leveled before heating to prevent the copper from rolling off when it melted. Throughout the experiment the temperature of the specimen was determined by the use of an optical pyrometer. Contact angles between the molten copper and the specimen were determined from photographs taken at intervals during the experiment. The specimen was usually held at 2000°F for 20 minutes. After cooling, it

was sectioned and examined metallographically as well as with an electron microprobe in order to investigate the interaction.

4340 Steel

Molten copper instantly wetted the surface of the 4340 steel. There was extensive penetration of the grain boundaries of the steel and some diffusion. (See Fig. 1) Copper penetrated along grain boundaries to a depth of about 2 mils and the steel within 200 to 400 microinches of the interface contained about 1 weight percent copper. The copper layer contained low levels (less than 0.5 weight percent) of chromium and nickel and about 3 weight percent iron. It is interesting to note that, while the chromium and nickel were uniformly distributed, the iron frequently was concentrated in particular regions.

Pyromet X-15

This metal behaved similarly to steel. It was wetted instantly with the molten copper and there also was grain boundary penetration to at least 2 mils. In this case, however, there was an unusual row of copper-rich beads running parallel to the interface at a depth of 400 to 600 microinches. There was no apparent communication with the bulk copper. The large number and constant depth of these beads argued against them being cross sections of grain boundary penetrations from the interface. (See Fig. 2) The diffusion of copper into the Pyromet was somewhat greater than it was with the steel, extending to depths of 1.2 to 1.6 mils.

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FIG. 1 Section through 4340 steel surface which had been in contact with molten copper for 20 minutes showing the grain boundary penetration. (750 X)

FIG. 2 Section through Pyromet X-15 surface which had been in contact with molten copper for 20 minutes showing the grain boundary penetration. (100 X)

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C.G. 27

In this case, the specimen was held at 2000°F for 30 minutes rather than 20 minutes as in the previously described experiments. At the outset, the copper did not wet the alloy; the initial contact angle was 122°. (See Fig. 3) It had reached 90° in 7.5 minutes and 60° in 30 minutes but these times are long as compared with contact times between bore and projectile even for rapid-firing aircraft guns which fire a great many rounds. However, if the temperature of the bore surface remained above the melting point of gilding metal during the latter part of a burst, there could be a much longer contact time with molten transferred gilding metal; it could be in the range of minutes with an 8,000 round barrel life for a gun with an 800 round/minute cyclic rate of fire if the burst lengths were long. The molten copper penetrated the C.G. 27 structure and dissolved it but in most locations, the original interface was still clearly visible. (See Fig. 4) The copper-colored phase was fairly uniform in composition containing about 5 weight percent each of nickel and iron and trace amounts of chromium. At great distances from the interface, grain boundaries were rich in chromium. The copper phase which had penetrated the C.G. 27 structure was filled with elongated light-colored regions. These were depleted in nickel and were rich in molybdenum as compared with C.G. 27 (7:1 ratio) when located near the original

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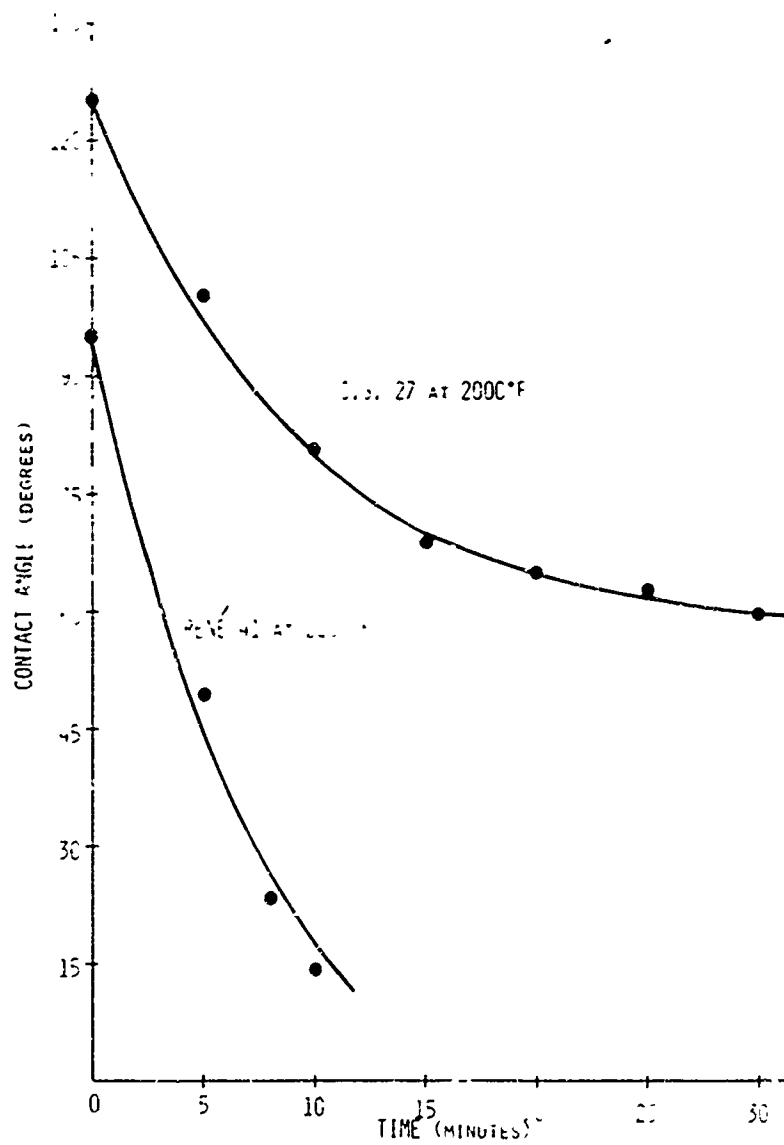
FIG. 3 Contact angles with molten copper as a function of time.

interface and rich in molybdenum as compared with C.G. 27 (7:1
ratio) when located near the original interface and rich
in iron as compared with C.C. 27 (1.3:1 ratio) when located
remote from the interface. Furthermore, copper was present
at the grain boundaries of the C.G. 27 at a considerable
depth below the new copper-phase interface. Therefore,
molten copper penetrates the C G. 27 structure along grain
boundaries destroying it by extracting nickel and iron.

René 41

In this case, the specimen was held at 2200° rather
than at 2000°F as in the previously described experiments.
The initial contact angle was 92°; it had reached 90° in
half a minute and 15° in ten. (See Fig. 3). On cooling,
the entire copper drop was filled with light-colored
dendrites which were usually rich in cobalt and/or chromium.
(See Fig. 5). The René was attacked by the molten copper
to produce an irregular interface owing to selective attack
on certain crystal faces. The attacked faces had dark gray
regions about 80 microinches behind the copper interfaces
when observed by means of back-scattered electrons. (See
Fig. 6). These gray regions were rich in chromium and
molybdenum and depleted in nickel. Fig. 6 shows a nickel
scan across one of these regions. There was quite a high
concentration of nickel at the copper interface and then
it is reduced to almost its concentration in the copper
phase within the gray band. Beyond the gray band it again

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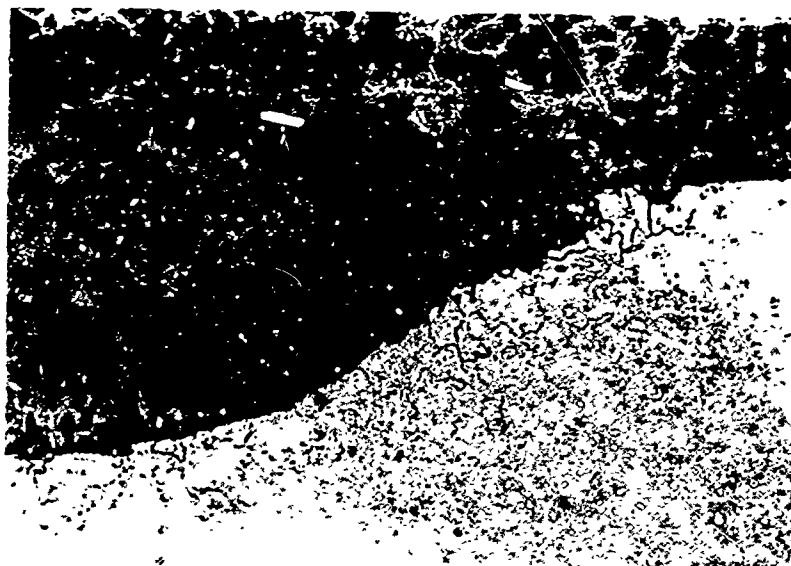
FIG. 4 Section through C.G. 27 surface which had been in contact with molten copper for 30 minutes showing the extensive interaction. (100 X)
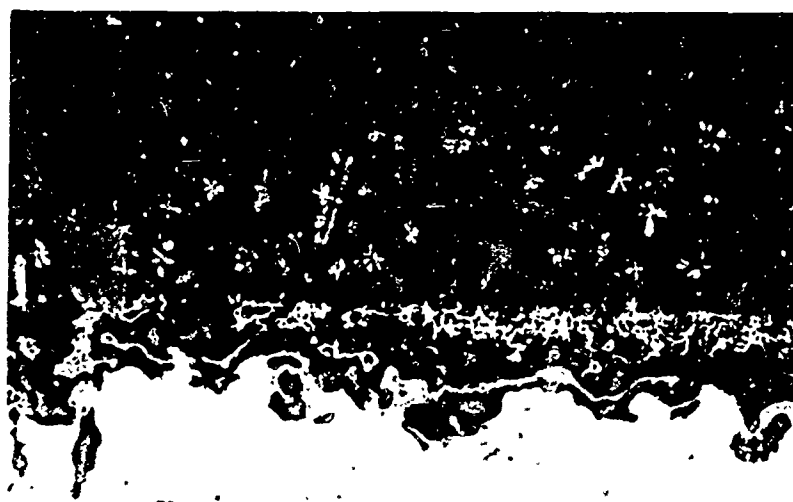
FIG. 5 Section through Rene 41 surface which had been in contact with molten copper for 20 minutes showing interaction and the dendrites present in the copper phase. (100 X)

increases to a relatively high value within the bulk René
41. It is difficult to see the reason for this odd dis-
tribution of nickel. The René 41 us ally contained copper
to about 400 microinches beyond the interface but there
was no measurable copper concentration gradient behind the
interfaces where the molybdenum-chromium rich gray phase
was absent.

A sessile drop experiment of short duration was also
run with René 41. This was the initial experiment where
gilding metal was used rather than unalloyed copper. When
the gilding metal melted at 1960°F, the zinc evaporated,
condensing on the window and obscuring the specimen. The
heat was turned off immediately but the gilding metal
remained molten for 1 or 2 minutes. The zinc content was
reduced to about 2 weight percent in this time. Even in
this relatively short time, there was a reaction zone
between the copper and René 41 of at least 4 mils. (See
Fig. 7). The copper phase contained 6 weight percent
nickel but no penetration of the base metal by copper
could be detected. Apparently, in this experiment, the
molten copper rapidly extracted nickel from the surface
of the René 41 but did not itself penetrate into the René
structure. The isolated regions within the interaction zone
shown in Fig. 8 contained the same elements as did the base
metal.

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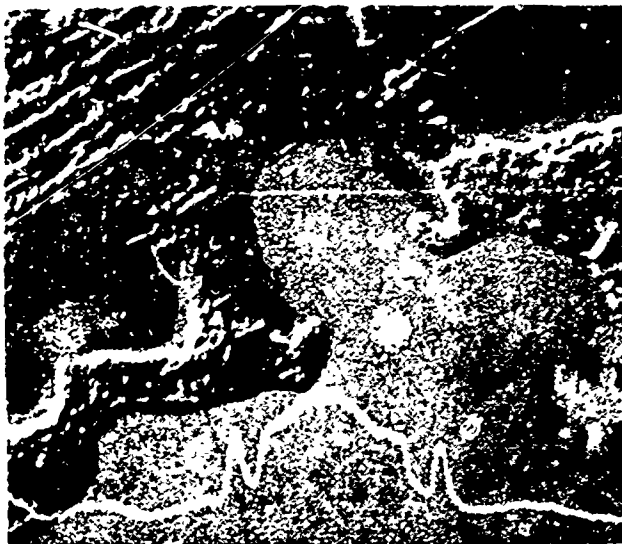
FIG. 6 Scanning electron micrograph of section through Rene 41-copper

interface showing interaction zone in the Rene. The superimposed graph

is the nickel concentration through the interface along the thin

straight white line. (730 X)

FIG. 7 Section through Rene 41 surface which had been in contact with

molten gilding metal for 1 to 2 minutes showing severe attack of the

Rene. (750 X)

Udimet 700

This alloy was wetted instantly with the molten copper and there was extensive interaction. The copper completely disappeared; it not only attacked the surface in contact with it, but it also flowed around and attacked the reverse side of the Udimet specimen. The depth of interaction was only limited by the amount of copper available. In many locations, the interaction zone was as much as 12 mils deep. The Udimet was completely converted into a system of dendrites. (See Fig. 8). There were penetrations of copper containing about 15 weight percent nickel and gray and metallic-appearing regions (See Fig. 9). The composition of the gray regions was 45 weight percent copper, 35 weight percent nickel, and the balance cobalt and chromium; the composition of the metallic-appearing regions was 20 weight percent copper, 50 weight percent nickel, and the balance cobalt and chromium. Apparently, the gray regions were edges of metallic grains. Not all the grain boundaries were visible because more could be identified by their relatively high copper contents on electron microprobe examination.

ACTUAL FIRING TESTS

Probably the best way to study the interaction of gilding metal with bore alloys is to use an actual firearm, the bore metal can be exposed to the action of molten gilding metal under the conditions of temperature and mechanical

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FIG. 8 Section through Udimet 700 surface which had been in contact with molten copper for 20 minutes showing interaction and the dendrites present in the copper phase. (100 X)

FIG. 9 Section through Udimet 700-copper interface showing the different regions in the attacked Udimet. (750 X)

deformation present in the bore of a gun during extended firing. The guns of greatest interest are the rapid-firing aircraft weapons because the barrels of these weapons must operate at high temperatures and are, therefore, potential applications for the advanced, high-temperature alloys. Since it would be prohibitively expensive to use actual aircraft guns with different alloy barrels in the experiments, the conditions of interest were obtained with the much smaller and more conveniently used 5.56mm M-16 rifle. The 5.56mm bullets are gilding metal jacketed and provided the same surface interactions as the rotating bands in the larger guns. A specially designed muzzle extension made of the test alloy was used and it was electrically heated before firing so that the high barrel temperature of a long burst could be simulated with a modest expenditure of actual rounds. The use of a test device on the end of the barrel had the advantage that it moved the hot test-section further away from the chamber where the propellent gases are most reactive and, therefore, the copper-bore metal reaction most obscured by their effects. With this experimental device, the interaction of gilding metal with the different test alloys at the conditions present in the barrel of a rapid-firing aircraft weapon can be studied conveniently and inexpensively.

Design of Test Device

The assembled test device affixed to the muzzle of an M-16 rifle is shown in Fig. 10. The device is disassembled in Fig. 11 to show the design of its component parts. The crux of the design is the test bore made in two pieces. There are a number of advantages to this design.

a. It allows specimens to be made of even the most difficultly machined alloys because they can be fabricated entirely by grinding.

b. The test bore is perfectly straight and its dimensions can be precisely controlled over its entire length.

c. Changes in the bore surface are easily observed without destroying the specimens.

d. Changes in the bore surface during the progress of the test firing can be followed by taking the device apart and examining it at intervals.

e. It is possible for half the bore circumference to be conventional gun steel and half the alloy to be studied. This will result in a steel specimen run at essentially the same conditions as the test alloy for comparison. In actual fact, C.G. 27, René 41, and Udimet 700 were all tested in this way. This procedure also has the advantage that only one of the more expensive test alloy specimens is required for an experiment. Caution should be used, however, with interpretation of relative erosion rates using this method. If one half of the bore becomes more severely eroded than

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FIG. 10 Assembled test device affixed to the muzzle of an M-16 rifle.

FIG. 11 Test device disassembled to show the design of its component parts.

the other, the test conditions on each specimen will no longer be the same.

The two test specimens were held together and in place by a taper ground on their reverse sides fitting into a mating taper in the holding fixture. The holding fixture was then bolted to a water-cooled flange which was screwed onto the rifle muzzle in place of the flash suppressor. Water-cooling was used to minimize any deterioration of the rifle barrel or interaction with the gilding metal before the bullet reached the test alloy and to eliminate the possibility of a "cook-off", i.e. discharge of the weapon owing to a high chamber temperature. The temperature of the test specimen was measured at a location near the exit end of the test bore by means of an iron-constantan thermocouple. A temperature measurement at this point will assure that the temperature of the specimen is sufficiently high and that it is similar from experiment to experiment but it will not measure the temperature at the entrance of the test bore. Before firing, this temperature will be considerably below the measured temperature owing to the heat-sink action of the water-cooled flange. It will, however, rapidly increase during the firing. The bore surface temperature can probably be best estimated by metallographic examination of the metal after the experiment.

The swaging action at the origin of rifling of a gun was simulated by making the test bore slightly smaller than the

diameter of the bullet. This produced the same mechanical working of the bullet as rifling without the complication and expense of having rifling in the test specimens. The diameter of the bore of the M-16 rifle was 0.2197 in. at its muzzle and 0.2198 in. at a point a half inch back from the muzzle; the diameter of the rifling was 0.2237 in. The diameters of the test bores were specified as between 0.2202 and 0.2210 in. The test bore diameter will increase by 0.0015 to 0.0017 in. on being heated to 1000°F., the temperature at the exit end of the test specimens when firing was begun. The expansion of the diameter at the bore entrance, which is the important location, however, would be less than this owing to the lower temperature at this location. If it was about 0.0008 in., the bullets would be swaged approximately 3 mils at six locations on their circumferences corresponding to the barrel rifling provided that the surfaces of the bullets extended to the bottoms of the rifling grooves. It is difficult to estimate the actual interference but from the appearance of the specimens after the experiment, there was a severe swaging action.

Experimental Procedure

The text device was assembled and the entrance end of the bore enlarged approximately 1 mil with a conical-shaped stone. A 2-mil asbestos paper washer was used between the test specimens and the cooling flange (except in the initial experiment with the 4340 steel) in order to provide some

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thermal insulation so that the entrance of the test bore
would be as hot as possible. The test specimens were
positioned in the holding fixture with the same orientation
as when they were finished-honed because it was found that
the other orientation resulted in a very slight mismatch.
The assembled test device was affixed to the muzzle of the
M-16 rifle and aligned carefully with the rifle bore by means
of a centering plug. The whole assembly was then clamped
into a fixture mounted in position at the test firing range.
The two halves of a cylindrical electric resistance furnace
were then clamped about the test device and the openings
between the furnace and the device plugged with wads of
asbestos paper. The cooling water was begun circulating
through the copper coil on the barrel flange and the specimen
temperature brought to 1000°F. When the exit end of the test
specimen had reached this temperature, the rifle barrel was
warm but not uncomfortable to the touch. A single round was
fired to insure that everything was in operating order. Then,
with as little delay as possible, the remaining 19 rounds in
the clip were fired in the automatic mode. The trigger of
the rifle was actuated by means of a solenoid so that the
firing could be controlled remotely. After cooling, the set-
up was disassembled and the specimens examined.

Results of Firing Tests

After the experiment, the entrance of the test bore was
found to be severely eroded and covered with a thick,

sometimes up to 5 mils, coating of transferred gilding metal.
(See Fig. 12). When a homogeneous test bore was used (4340
steel and Pyromet X-15) the erosion was somewhat deeper on
one half than on the other probably because the test bore
had not been exactly centered during the experiment. There-
fore, the conclusion that a test material erodes either more
or less than steel drawn from a comparison of the relative
erosions of bore halves run at the same time must be viewed
with caution.

The transferred gilding metal in the eroded zone was
usually (but not always) strongly layered with the layers
being separated by thin, dark-colored bands. (See Fig. 13).
The individual layers had been evidently transferred from
successive bullets. On electron microprobe examination,
the transferred gilding metal was found to contain from 5
to 10 weight percent zinc; evidently some of the zinc was
frequently volatilized from the molten gilding metal.
Sometimes the transferred gilding metal contained up to 6
weight percent sulfur but sometimes none could be detected
and sometimes a strong lead signal was obtained but some-
times no lead could be detected. Usually, the sulfur and
lead were homogeneously distributed throughout the trans-
ferred layer with occasional local concentrations of one
or both. As a general rule, there seemed to be no par-
ticular correlation between the strength of the sulfur and
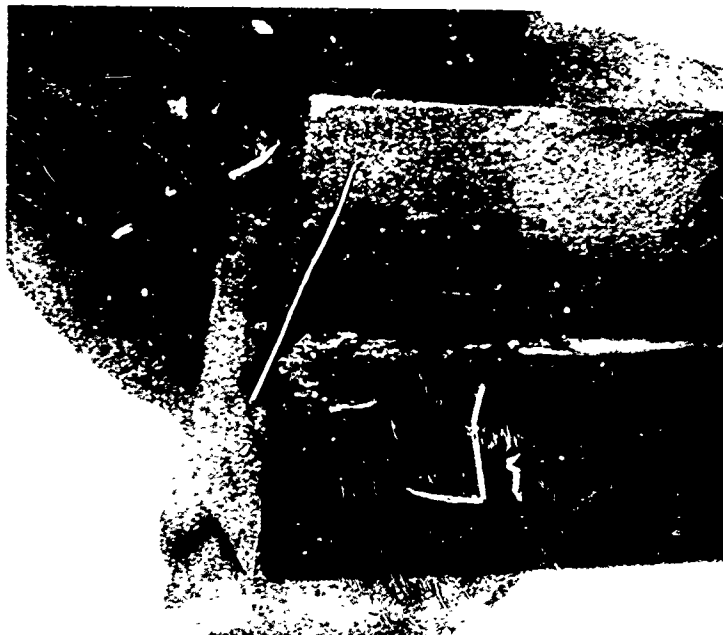lead signals nor did their concentrations correspond with the

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FIG. 12 Entrance of the C.G. 27 test bore after firing showing erosion
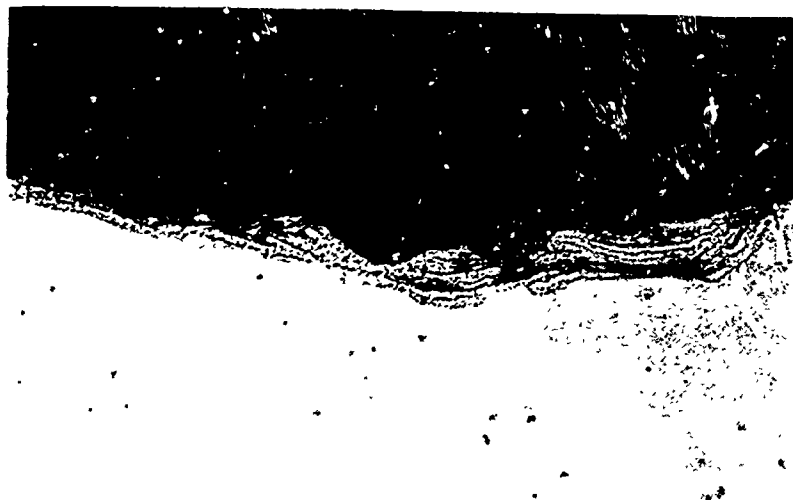and transferred gilding metal.

FIG. 13 Section through Udimet 700 specimen at the eroded zone showing
layered structure of transferred gilding metal. (100 X)

dark-colored bands. In one case, however, the dark bands produced a lead-to-sulfur ratio in good agreement with the ratio for lead sulfide. The presence of sulfur in the surrounding copper, however, prevented a positive identification. In some cases, there was a thin coating of lead on the surface of the transferred gilding metal.

In their study of fired gun tubes, Zies and Marsh [1] found that frequently a pronounced layered structure was evident, consisting of alternate deposits of reaction products and other debris and of flows of copper. Sulfur and both copper and zinc sulfides were found in the transferred gilding metal as was lead sulfide. However, whether or not there was any correspondence of these materials with the banded structure could not be determined because the required analytical tools were not available at the time.

The eroded zones at the entrances of the test bores appeared as though "flame-cut"; there were no sliding marks apparent on the surfaces. (See Fig. 14) Fig. 15 is a typical electron micrograph of the surface of the transferred gilding metal in the eroded zone. It is "knobby" in appearance and there are no sliding marks or micro-directionality. This together with the fact that the gilding metal penetrated into

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[1] Zies, E. G. and Marsh, C. A., "The Products of Gun Erosion", Hypervelocity Guns and the Control of Erosion, Summary Technical Report of Division I, NDRC, 244 (1946)

FIG. 14 Front edge of erosion zone of 4340 steel specimen showing "flame-cut" appearance. (100 X)

FIG. 15 Electron micrograph of a replica of the surface of the
transferred gilding metal in the eroded zone of the René 41 specimen.
(6500 X)

the crack between the two specimen halves, proves that it was transferred as molten metal.

4340 Steel

There was a thin layer of worked metal at the interface beneath the transferred gilding metal which showed considerably smaller grain size. It ranged from 30 to 300 microinches in thickness. However, there was no evidence of melting of the steel. (See Fig. 16). The layer of worked metal was appreciatly softer than was the bulk steel as is shown in Fig. 17. There had been intimate contact between the steel and the molten gilding metal in the erosion zone during the firing but there was no detectable interpenetration of the two metals. X-ray intensities characteristic of iron and copper as a function of beam position are shown in Fig. 18. The probe beam was approximately 80 microinches in diameter so interpenetration, if any, could not have exceeded about 40 microinches.

Pyromet X-15

There was a "white-etching" layer, sometimes as thick as 400 microinches, under the transferred gilding metal and a "thermally altered" layer beneath it. (See Fig. 19) Between the white-etching layer and the thermally altered layer, there was a thin "precipitated" band. The appearance of the specimen was similar to that of authentic fired steel gun tubes. The white-etching layer on over-etching was found to be comprised of small, undeformed grains. Evidently,

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FIG. 16 Section through the eroded zone of a 4340 steel specimen showing thin layer of worked metal at the surface. (100 X)
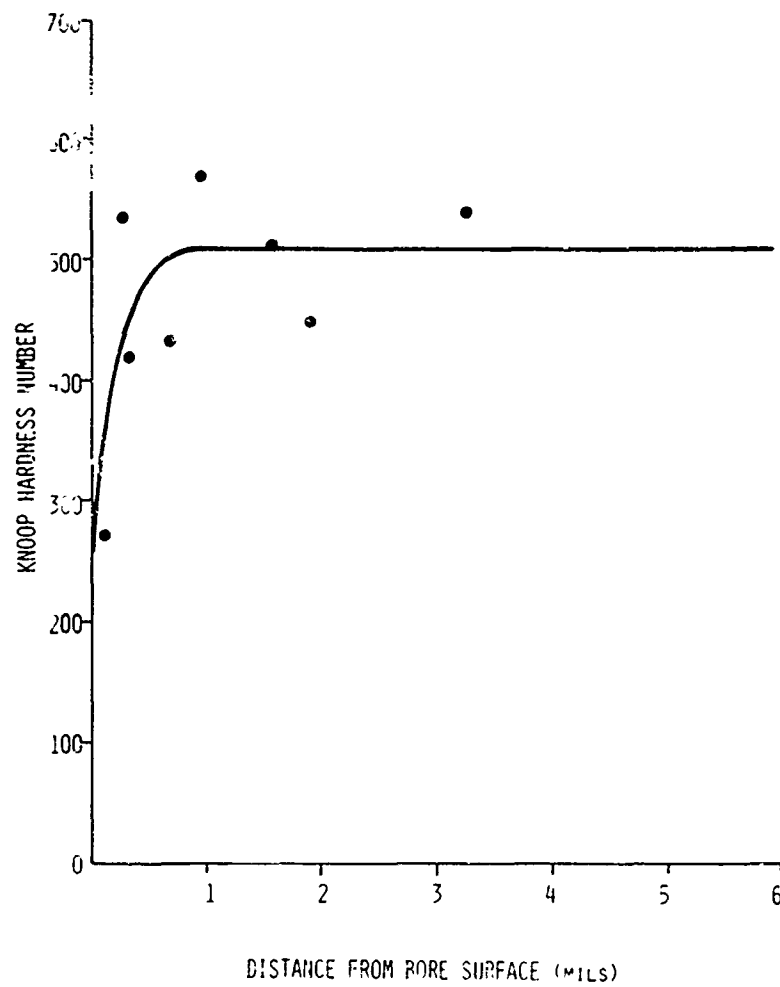
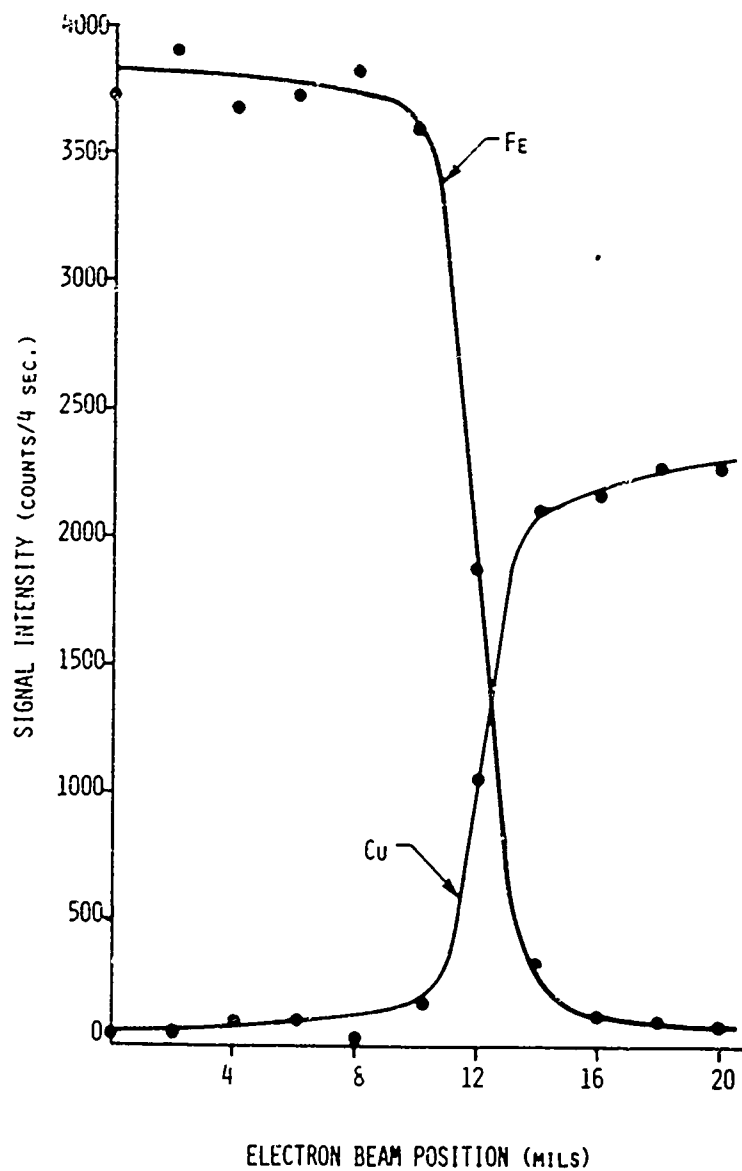FIG. 17 Hardness through 4340 steel beneath the eroded zone as a function of distance from bore surface.

FIG. 18 X-ray intensities characteristic of iron and copper across a section through the eroded zone of a 4340 steel specimen showing lack of interpenetration .

FIG. 19 Section through Pyromet X-15 specimen at the eroded zone
showing "white-etching" layer, "thermally altered" layer, and the thin
"Precipitated" band between them. (1000 X)

this layer had been produced by surface melting of the bore.
As in the case of the steel, the surface metal was considerably
softer than was the bulk metal. With the Pyromet, however,
the softer surface layer was four times as thick. (See
Fig. 20) At two locations in the eroded zone, features were
observed which were identified as bands of adiabatic shear.
(See Fig. 21) These features were narrow, white-etching
bands with sharp boundaries which, in one case, extended 13
to 14 mils into the base metal before becoming diffuse and
disappearing. They were comprised of small, undeformed
crystals and were contiguous and optically identical with
the surface white-etching layer. In the one case, the metal
on one side had been displaced a distance of 1.3 mils where
the band intersected the surface.

As with the steel, there was no detectable inter-
penetration of the copper and bore metal. X-ray intensities
characteristic of iron, cobalt, chromium, and copper as a
function of beam position are shown in Fig. 22. There could
have been some depletion of chromium of a thin surface layer.
The sharper demarcation between the metals in this case was
attributed to more intimate contact between the bore metal
and the transferred gilding metal at the particular location
examined rather than to a real difference in penetration.

C.G. 27

The metal beneath the transferred gilding metal in the
eroded zone sometimes showed a thin white-etching layer (up to

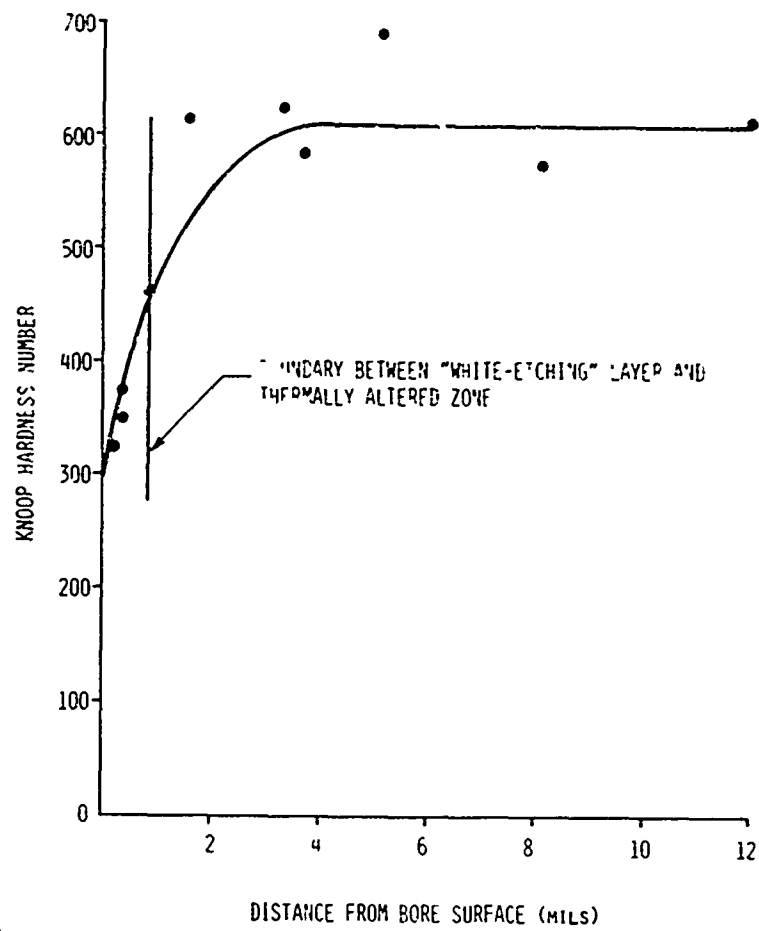FIG. 20 Hardness through Pyromet X-15 beneath the eroded zone as a function of distance from bore surface.

FIG. 21 Section through Pyromet X-15 specimen at the eroded zone
showing surface intersection of a band of adiabatic shear. (750 X)
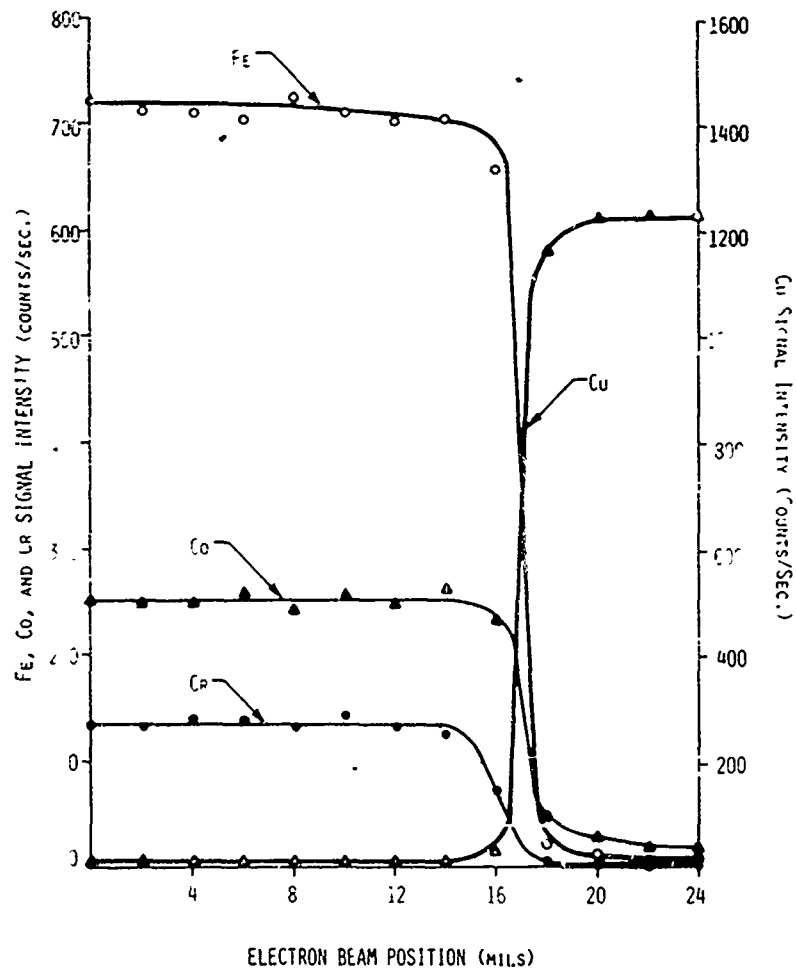
FIG. 22 X-ray intensities characteristic of iron, cobalt, chromium, and copper across a section through the eroded zone of the Pyromet X-15 specimen showing lack of interpenetration.

about 100 microinches) and the surface grains appeared some-
what elongated in some locations. (See Fig. 23.) Other than
this, there were no changes in the microstructure as a result
of the firing. Furthermore, there was no electron microprobe
evidence for any interaction between the molten gilding metal
and the C.G. 27.

René 41

The metal beneath the transferred gilding metal in the
eroded zone showed a large number of large cracks (See Fig.
24) and bands of adiabatic shear (See Fig. 25) approximately
parallel with the surface and a great many dark-etching slip
lines but there was no evidence of significant surface melt
ing. In addition, there were many small cracks extending
from the surface down into the bulk metal. (See Fig. 26.)
These cracks followed the grain boundaries going around the
carbide grains which were there but the grains of titanium
carbonitride were usually broken. While this extensive damage
to the René 41 appeared to be mechanical, it was possible
that it could have been the result of interaction with the
molten gilding metal. Therefore, firing experiment was
carried out using soft-iron bullets rather than the con-
ventional gilding metal jacketed lead bullets.

After this firing, the René 41 did not show the serious
erosion that was observed with the gilding metal jacketed
bullets and no large cracks parallel with the bore surface

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FIG. 23 Section through C.G. 27 specimen at the eroded zone showing
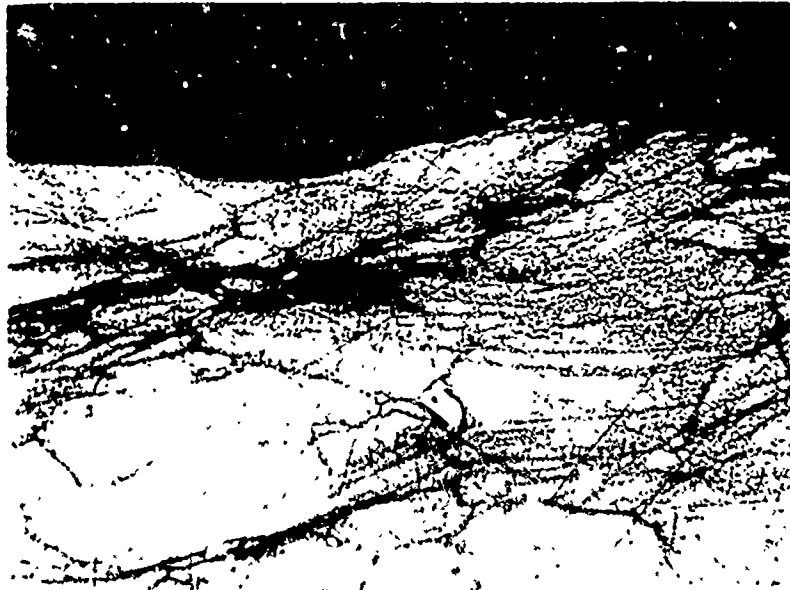thin "white etching" layer. (1000X)

FIG. 24 Section through Rene 41 specimen at the eroded zone showing
one of the large cracks which are approximately parallel with the
surface. (1000 X)

FIG. 25   Section through René 41 specimen at the eroded zone showing
one of the bands of adiabatic shear which are approximately parallel
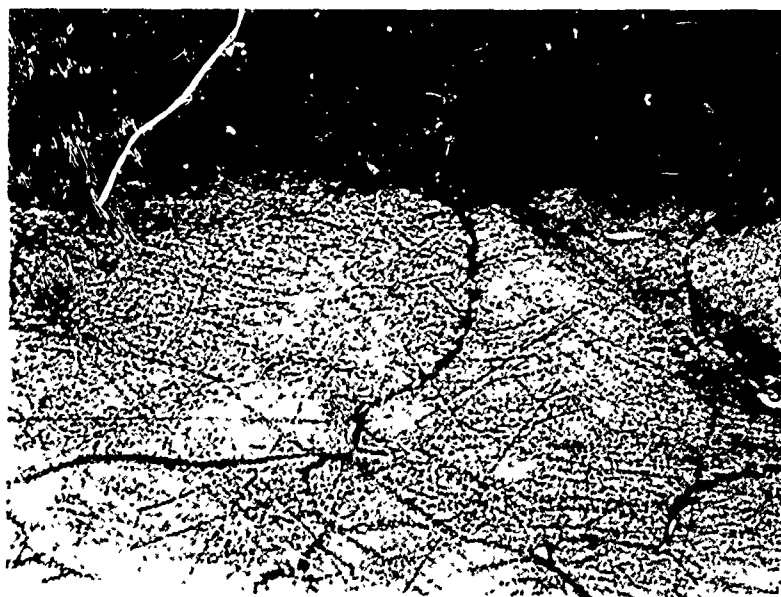with the surface.   (1000 X)

FIG. 26   Section through René 41 specimen at the eroded zone showing
the thin cracks which penetrate into the interior along grain
boundaries.   (1000 X)

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could be found. However, there were many of the small cracks extending down from the surface into the bulk metal; one was even initiated a short distance from the bore on the parting line between the specimens. Therefore, while the production of the small cracks was indeed mechanical, the extensive erosion damage and large cracks were a result of interaction with the molten gilding metal. However, interpenetration of copper and René 41 was not detected and no copper was found at the grain boundaries of the specimen used with gilding metal jacketed bullets.

Udimet 700

The metal beneath the transferred gilding metal in the eroded zone appeared mechanically disturbed and the surface grains were elongated and distorted. Furthermore, there were some slip lines in the surface metal and here and there some very small regions of white-etching metal. (See Fig. 27.) However, there was no surface melting of the Udimet 700 and no interpenetration of the gilding metal and the bore metal.

Because of the very small amount of erosion of the Udimet 700 in the 20 round firing test, a more extended firing test was carried out. In this test, the temperature of the test device was raised to 1200°F before firing was begun instead of 1000°F as in the previous firing tests. When this temperature had been attained (which appeared to be about the limit for the electric furnace used) seven 20 round clips were fired in the automatic mode as rapidly as possible.
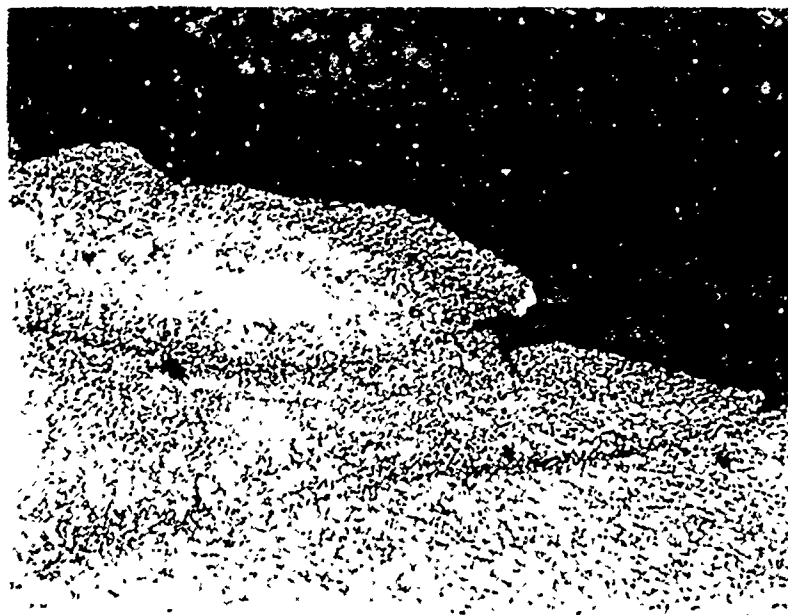
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FIG. 27 Section through Udimet 700 specimen at the eroded zone showing
mechanically disturbed surface and dark-colored slip lines. (1000 X)

There were three misfires necessitating recocking the rifle which required 5 to 7 seconds each instance. The entire string of 137 rounds required about 3 minutes.

After the experiment, there was very little erosion and the Udimet 700 appeared identical to the specimen from the 20 round test. Again, no penetration could be detected along grain boundaries or in the bulk of the bore metal by means of the electron microprobe and, furthermore, nickel and cobalt were not present in the transferred gilding metal in con-centrations greater than 0.5 weight percent.

Comparison of Amounts of Erosion

Most of the conditions in the test bore such as bore and projectile skin temperatures, relative velocity, and gas environment were probably the same as those in an actual gun barrel but the mechanical stress on the bore metal was doubt-less significantly greater at least at the entrance. This was evidenced by the severe erosion observed in just 20 rounds. Perhaps this was the reason that the erosion observed in these experiments did not completely correspond with that observed in tests with actual gun barrels. If this were the case, probably closer correspondence could be achieved by using a slightly larger test bore so that the swaging action would not be as severe.

The erosion zone with the Pyromet X-15 was significantly shorter but deeper than with the 4340 steel. Perhaps this indicated that the Pyromet is more erosion resistant but

not as stress resistant. This conjecture is strengthened by the adiabatic shear lines in the specimen after testing. In the machine gun barrel tests Pyromet X-15 had shown greater erosion resistance than did the steel.

The C.G. 27 showed about the same erosion as did the steel in the present experiments although it had performed much better than did steel as a barrel for a 30mm aircraft cannon. The severe coppering of the test bore along its entire length observed in the present experiments might indicate a potential problem with the use of C.G. 27 barrels. (See Fig. 28.)

The René 41 was much more eroded than was the steel. This severe erosion can be attributed to interaction with molten gilding metal because much less erosion was obtained with soft-iron bullets. This corroborates the machine gun barrel experiments where catastropic erosion resulted when a severe firing schedule was used.

The Udimet 700 showed very little erosion even after a test of 137 rapid-fire rounds. However, the bore was heavily "coppered" after the experiment as was the C.G. 27 also perhaps indicating a potential problem with the use of Udimet 700 barrels.

CONCLUSION

There was no interaction of copper-containing rotating band material with 4340 steel, Pyromet X-15, C.G. 27, nor

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FIG. 28 Bore of C.G. 27 specimen 3/4 in. from entrance showing severe
"coppering". (100 X)

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Udimet 700 detected in the firing experiments even though
C.G. 27 and especially Udimet 700 interacted strongly in
sessile-drop experiments. The contact times were very short
in the firing experiments even if the test bore surface
remained above the melting point for gilding metal during
the latter part of the burst. René 41, which did not inter-
act with copper nearly as dramatically in the sessile-drop
experiments as did Udimet 700, did, however, show serious
degradation as a result of attack by molten gilding metal in
the test bore. This corroborates earlier gun barrel experi-
ments. The mechanism of this attack is not clear. However,
from the sessile-drop experiments, it may be the depletion
of nickel from the surface layer of the René rather than
alloying of copper with bore metal as suggested by Harlow
and Kimball [7]

In the firing experiments it was found that, contrary
to what might be expected, coating of the bore with gilding
metal beyond the erosion zone could not be predicted from
the wetability of the bore metal with copper. 4340 Steel,
Pyromet X-15, and Udimet 700 all wetted instantly but, of
these, only Udimet 700 showed significant gilding metal
transfer throughout the bore. On the other hand, C.G. 27,
which was not initially wetted with molten copper, probably
showed the most severe "coppering".

[7] Harlow, R. A. and Kimball, R. C., "Aeronutronic Advanced Gun
Barrel Development Program", Symposium on Gun Tube Erosion
and Control, Watervliet Arsenal, Watervliet, N.Y., Feb 25, '70.

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While these experiments were not designed to compare the erosions of bore metals, useful data on erosion resistance could, nevertheless, be obtained. Rene 41, which showed catastrophic erosion in a gun barrel also showed severe erosion in the present experiments. It also showed brittle behavior in the highly stressed region; this had not been noticed in the previous gun barrel experiments. The experiments, however, were not suitable for distinguishing among bore metals of more similar erosion resistance. 4340 Steel, Pyromet X-15, and C.G. 27 all exhibited about the same amounts of erosion. Udimet 700 showed strikingly little erosion even at a higher initial temperature and a much longer burst length. Of the bore metals tested, it showed the best erosion resistance by far.

RECOMMENDATIONS FOR FURTHER RESEARCH

This kind of testing of potential bore metals is convenient and very inexpensive as compared with the usual long-duration firing tests employing actual gun barrels. Therefore, while it will not supplant actual barrel testing, it should certainly be done before a full-scale barrel test is planned. In this study, the various alloys were tested only in a preliminary manner; they should be studied more thoroughly if they are actively under consideration for barrels for rapid-firing weapons. In addition, it might be useful to investigate a wide range of potential bore metals because it is relatively inexpensive with these methods.

The effect of rotating bands and bullet jackets of materials other than gilding metal could be studied efficaciously using these methods. There is a supply of 5.56mm bullets of both soft iron and aluminum on hand so these metals would be easily studied.

With a reasonable sample size and probably with a somewhat larger test bore diameter, firing tests such as those described in this report could be used to compare erosion rates of different materials or under different conditions. High bore temperatures characteristic of long bursts, for example, could be conveniently attained without the expenditure of large quantities of ammunition.

The use of the present test bore diameter results in significantly more impact damage to the test bore entrance than does the constriction in a barrel at the origin of rifling. Therefore, firing tests with this test geometry could be used to evaluate the adherence and durability under severe impact of electroplates and other barrel coatings.

ACKNOWLEDGEMENTS